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# GRI: THE GAMMA-RAY IMAGER MISSION

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## ABSTRACT

With the INTEGRAL observatory, ESA has provided a unique tool to the astronomical community revealing hundreds of sources, new classes of objects, extraordinary views of antimatter annihilation in our Galaxy, and fingerprints of recent nucleosynthesis processes. While INTEGRAL provides the global overview over the soft gamma-ray sky, there is a growing need to perform deeper, more focused investigations of gamma-ray sources. In soft X-rays a comparable step was taken going from the Einstein and the EXOSAT satellites to the Chandra and XMM/Newton observatories. Technological advances in the past years in the domain of gamma-ray focusing using Laue diffraction have paved the way towards a new gamma-ray mission, providing major improvements regarding sensitivity and angular resolution. Such a future Gamma-Ray Imager will allow studies of particle acceleration processes and explosion physics in unprecedented detail, providing essential clues on the innermost nature of the most violent and most energetic processes in the Universe.

Key words: gamma-ray focusing; crystal lens telescopes; mission concepts.

## 1. FROM INTEGRAL TO GRI

The present conference has nicely illustrated how INTEGRAL has changed our vision of the gamma-ray sky. The telescopes aboard the satellite have revealed hundreds of sources of different types, new classes of objects, extraordinary and puzzling views of antimatter annihilation in our Galaxy, and fingerprints of recent nucleosynthesis processes. With the wide fields of view of the IBIS and SPI telescopes, INTEGRAL is an exploratory-type mission that allows extensive surveys of the hard X-ray and soft gamma-ray sky, providing a census of the source populations and first-ever allsky maps in this interesting energy range. The good health of the instruments after 4

years of operations allows the continuation of the exploration during the upcoming years, enabling INTEGRAL to provide the most complete and detailed survey ever, which will be a landmark for the discipline throughout the next decades.

Based on the INTEGRAL discoveries and achievements, there is now a growing need to perform more focused studies of the observed phenomena. High-sensitivity investigations of point sources, such as compact objects, pulsars, and active galactic nuclei, should help to uncover their yet poorly understood emission mechanisms. A deep survey of the galactic bulge region with sufficiently high-angular resolution should shed light on the still mysterious source of positrons. And a sensitivity leap in the domain of gamma-ray lines should allow the detection of nucleosynthesis products in individual supernova events, providing direct insights into the physics of the exploding stars.

Technological advances in the past years in the domain of gamma-ray focusing using Laue diffraction have paved the way towards a new gamma-ray mission that can fulfil these requirements. Laboratory work and balloon campaigns have provided the proof-of-principle for using Laue lenses as focusing devices in gamma-ray telescopes [33, 14], and concept studies by CNES and ESA have demonstrated that such an instrument is technically feasible and affordable [11, 6]. Complemented by a hard X-ray telescope based on a single-reflection multilayer coated concentrator, a broad-band energy coverage can be achieved that allows detailed studies of astrophysical sources at unprecedented sensitivity and angular resolution, from a few tens of keV up to at least 1 MeV.

Bringing our scientific requirements into the context of these technological achievements, we started a common effort to define the scenario for a future gamma-ray mission that we baptised the *Gamma-Ray Imager* (GRI). In this paper we present our scientific motivations, the science requirements for the mission, and a mission sketch. The GRI mission fits well into the framework of ESA's Cosmic Vision 2015-2025 planning, and it will provide a perfect successor for the INTEGRAL mission. While INTEGRAL provides the general overview over the hard X-ray and soft gamma-ray sky, GRI will allow a zoom-in, unveiling the physics of cosmic explosions and cosmic accelerators that dominate the high-energy Universe.

<sup>\*2</sup> the GRI consortium is composed of members from the countries Belgium, China, Denmark, France, Germany, Italy, Ireland, Poland, Portugal, Russia, Spain, The Netherlands, United Kingdom, and the United States. A complete list of GRI consortium members can be found on <http://gri.rm.iasf.cnr.it/>.

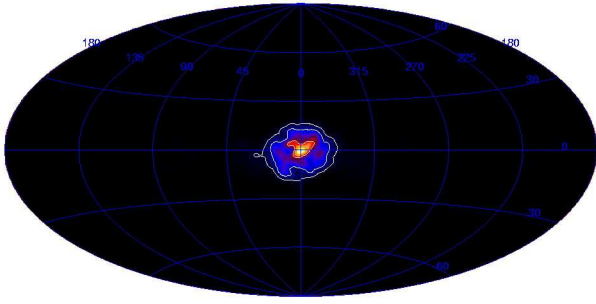


Figure 1. First all-sky map of 511 keV positron-electron annihilation radiation as observed by the SPI telescope aboard INTEGRAL [20].

## 2. COSMIC EXPLOSIONS

### 2.1. Understanding Type Ia supernovae

Although hundreds of Type Ia supernovae are observed each year, and although their optical lightcurves and spectra are studied in great detail, the intimate nature of these events is still unknown. Following common wisdom, Type Ia supernovae are believed to arise in binary systems where matter is accreted from a normal star onto a white dwarf. Once the white dwarf exceeds the Chandrasekhar mass limit a thermonuclear runaway occurs that leads to its incineration and disruption. However, attempts to model the accretion process have difficulties to allow for sufficient mass accretion that would push the white dwarf over its stability limit [17]. Even worse, there is no firm clue that Type Ia progenitors are indeed binary systems composed of a white dwarf and a normal star. Alternatively, the merging of two white dwarfs in a close binary system could also explain the observable features of Type Ia events [24]. Finally, the explosion mechanism of the white dwarf is only poorly understood, principally due to the impossibility of reliably modelling the nuclear flame propagation in such objects [17].

In view of all these uncertainties it seems more than surprising that Type Ia are widely considered as standard candles. Yet, it is this standard candle assumption that is the basis of one of the fundamental discoveries of the last decade: the accelerating expansion of the Universe [30]. Although empirical corrections to the observed optical lightcurves seem to allow for some kind of standardization, there is increasing evidence that Type Ia supernovae are not an homogeneous class of objects [26].

Gamma-ray observation of Type Ia supernovae provide a new and unique view of these events. Nucleosynthetic products of the thermonuclear runaway lead to a rich spectrum of gamma-ray line and continuum emission that contains a wealth of information on the progenitor system, the explosion mechanism, the system configuration, and its evolution. In particular, the radioactive decays of  $^{56}\text{Ni}$  and  $^{56}\text{Co}$ , which power the optical lightcurve that is so crucial for the cosmological interpretation of

distant Type Ia events, can be directly observed in the gamma-ray domain, allowing to pinpoint the underlying progenitor and explosion scenario. The comparison of the gamma-ray to the optical lightcurve will provide direct information about energy recycling in the supernova envelope that will allow a physical (and not only empirical) calibration of Type Ia events as standard candles.

In addition to line intensities and lightcurves, the shapes of the gamma-ray lines hold important information about the explosion dynamics and the matter stratification in the system. Measuring the line shapes (and their time evolution) will allow the distinction between the different explosion scenarios, ultimately revealing the mechanism that creates these violent events in the Universe [13].

### 2.2. Unveiling the origin of galactic positrons

The unprecedented imaging and spectroscopy capabilities of the spectrometer SPI aboard INTEGRAL have now provided for the first time an all-sky image of the distribution of 511 keV positron-electron annihilation [20] (cf. Fig. 1). The outcome of this survey is astonishing: 511 keV line emission is primarily seen towards the bulge region of our Galaxy, while the rest of the sky remains surprisingly dark. Only a weak glimmer of 511 keV emission is perceptible from the disk of the Galaxy, much less than expected from stellar populations following the global mass distribution of the Galaxy. In other words, positron annihilation seems to be greatly enhanced in the bulge with respect to the disk of the Galaxy.

A detailed analysis of the 511 keV line shape measured by SPI has also provided interesting insights into the annihilation physics [9]. At least two components have been identified, indicating that positron annihilation takes place in a partially ionized medium. This clearly demonstrated that precise 511 keV line shape measurements provide important insights into the distribution of the various phases of the interstellar medium (ISM) [18].

While INTEGRAL has set the global picture of galactic positron annihilation, the source of the positrons still remains mysterious. Expected 511 keV line flux levels from individual source candidates are (slightly) below the sensitivity of the instruments aboard INTEGRAL. With its enhanced sensitivity, point-like 511 keV line emission from individual objects will get into reach of GRI, enabling the measurement of electron-positron annihilation in individual candidate sources, such as compact binaries, pulsars, supernova remnants or novae.

The discovery of individual positron sources and the measurement of their positron production rates would provide a breakthrough in gamma-ray astronomy. The search for the 511 keV line in individual objects is therefore a primary objective of the GRI mission. The measurement of the 511 keV line in individual objects provides also an important diagnostics tool, allowing to constrain the physical conditions and eventually the plasma composition in the observed sources.

### 2.3. Understanding core-collapse explosions

Gamma-ray line and continuum observations address some of the most fundamental questions of core-collapse supernovae: how and where the large neutrino fluxes couple to the stellar ejecta; how asymmetric the explosions are, including whether jets form; and what are quantitative nucleosynthesis yields from both static and explosive burning processes?

The ejected mass of  $^{44}\text{Ti}$ , which is produced in the innermost ejecta and fallback matter that experiences the alpha-rich freezeout of nuclear statistical equilibrium, could be measured with GRI to a precision of several percent in SN 1987A. Along with other isotopic yields already known, this will provide an unprecedented constraint on models of that event.  $^{44}\text{Ti}$  can also be measured and mapped, in angle and radial velocity, in several historical galactic supernova remnants. These measurements will help clarify the ejection dynamics, including how common jets initiated by the core collapse are.

Wide-field gamma-ray instruments have shown the global diffuse emission from long-lived isotopes  $^{26}\text{Al}$  and  $^{60}\text{Fe}$ , illustrating clearly ongoing galactic nucleosynthesis. A necessary complement to these measurements are high-sensitivity ones of the yields of these isotopes from individual supernovae. GRI should determine these yields, and map the line emission across several nearby supernova remnants, shedding further light on the ejection dynamics. It is also likely that the nucleosynthesis of these isotopes in hydrostatic burning phases will be revealed by observations of individual nearby massive stars with high mass-loss rates.

For rare nearby supernovae, within a few Mpc, we will be given a glimpse of nucleosynthesis and dynamics from short-lived isotopes  $^{56}\text{Ni}$ , and  $^{57}\text{Ni}$ , as was the case for SN 1987A in the LMC. In that event we saw that a few percent of the core radioactivity was somehow transported to low-optical depth regions, perhaps surprising mostly receding from us, but there could be quite some variety, especially if jets or other extensive mixing mechanisms are ubiquitous.

### 2.4. Nova nucleosynthesis

Classical novae are another site of explosive nucleosynthesis that is still only partially understood [16]. Although observed elemental abundances in nova ejecta are relatively well matched by theoretical models, the observed amount of matter that is ejected substantially exceeds expectations. How well do we really understand the physics of classical novae?

Radioactive isotopes that are produced during the nova explosion can serve as tracer elements to study these events. Gamma-ray lines are expected from relatively long living isotopes, such as  $^7\text{Be}$  and  $^{22}\text{Na}$ , and from positron annihilation of  $\beta^+$ -decay positrons arising from

the short living  $^{13}\text{N}$  and  $^{18}\text{F}$  isotopes. Observation of the gamma-ray lines that arise from these isotopes may improve our insight into the physical processes that govern the explosion. In particular, they provide information on the composition of the white dwarf outer layers, the mixing of the envelope during the explosion, and the nucleosynthetic yields. Observing a sizeable sample of galactic nova events in gamma-rays should considerably improve our understanding of the processes at work, and help to better understand the underlying physics.

## 3. COSMIC ACCELERATORS

### 3.1. The link between accretion and ejection

As a general rule, accretion in astrophysical systems is often accompanied by mass outflows, which in the high-energy domain take the form of (highly) relativistic jets. Accreting objects are therefore powerful particle accelerators, that can manifest on the galactic scale as microquasars, or on the cosmological scale, as active galactic nuclei, such as Seyfert galaxies and Blazars.

Although the phenomenon is relatively widespread, the jet formation process is still poorly understood. It is still unclear how the energy reservoir of an accreting system is transformed in an outflow of relativistic particles. Jets are not always persistent but often transient phenomena, and it is still not known what triggers the sporadic outbursts in accreting systems. Also, the collimation of the jets is poorly understood, and in general, the composition of the accelerated particle plasma is not known (electron-ion plasma, electron-positron pair plasma). Finally, the radiation processes that occur in jets are not well established.

Observations in the gamma-ray domain are able to provide a number of clues to these questions. Gamma-rays probe the innermost regions of the accreting systems that are not accessible in other wavebands, providing the closest view to the accelerating engine. Time variability and polarization studies provide important insights into the physical processes and the geometry that govern the acceleration site. The accelerated plasma may reveal its nature through characteristic nuclear and/or annihilation line features which may help to settle the question about the nature of the accelerated plasma.

### 3.2. The origin of galactic soft $\gamma$ -ray emission

For decades, the nature of the galactic hard X-ray ( $>15$  keV) emission has been one of the most challenging mysteries in the field. The INTEGRAL imager IBIS has now finally solved this puzzle. Below  $\sim 100$  keV, about 90% of the emission has been resolved into point sources, settling the debate about the primary origin of the emission [23].

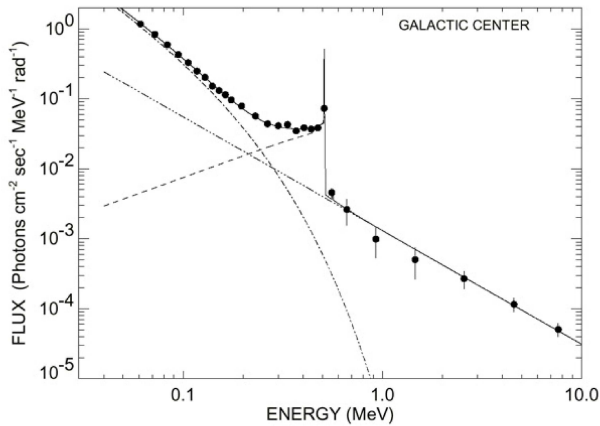


Figure 2. OSSE hard X-ray and soft  $\gamma$ -ray spectrum of the Galactic Centre region [19]. The spectrum is explained by 3 components: an exponentially cut-off powerlaw dominating below  $\sim 200$  keV, a powerlaw ( $\sim E^{-1.7}$ ) dominating above 511 keV, and a triangular-shaped positronium continuum component plus a narrow line at 511 keV.

At higher energies, say above  $\sim 200$  keV, the situation is less clear. In this domain, only a small fraction of the galactic emission has so far been resolved into point sources, and the nature of the bulk of the galactic emission is not entirely explained. That a new kind of object or emission mechanism should be at work in this domain is already suggested by the change of the slope of the galactic emission spectrum (cf. Fig. 2). While below  $\sim 200$  keV the spectrum can be explained by a superposition of Comptonisation spectra from individual point sources, the spectrum turns into a powerlaw above this energy, which is reminiscent of particle acceleration processes. Identifying the source of this particle acceleration process, i.e. identifying the origin of the galactic soft gamma-ray emission, is one of the major goals of GRI.

One of the strategies to resolve this puzzle is to follow the successful road shown by INTEGRAL for the hard X-ray emission: trying to resolve the emission into individual point sources. Indeed, a number of galactic sources show powerlaw spectra in the gamma-ray band, such as supernova remnants, like the Crab nebula, or some of the black-hole binary systems, like Cyg X-1 [27]. Searching for the hard powerlaw emission tails in these objects is therefore a key objective for GRI.

### 3.3. The origin of the soft $\gamma$ -ray background

After the achievements of XMM-Newton and Chandra, the origin of the cosmic X-ray background (CXB) is now basically solved for energies close to a few keV. Below 8 keV about  $\gtrsim 80\%$  of the emission has been resolved into individual sources, which have been identified as active galactic nuclei (AGN) [15]. Above  $\sim 8$  keV, however, only  $\lesssim 50\%$  of the CXB has been resolved into sources [34], while in the 20–100 keV hard X-ray band, where

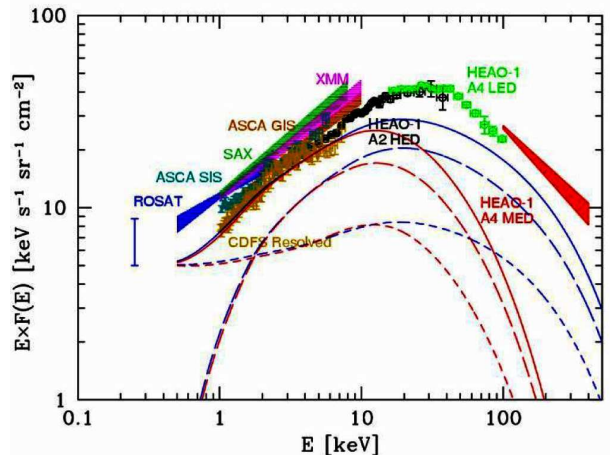


Figure 3. The 0.25–400 keV cosmic background spectrum fitted with synthesis models [10]. None of the models provides a satisfactory fit of the observations.

IBIS is most sensitive, only  $\sim 1\%$  of the emission has been resolved [3]. Above this energy, in the soft  $\gamma$ -ray band, basically nothing is known about the nature of the cosmic background radiation.

While the situation in the hard X-ray band ( $\lesssim 100$  keV) may change after the launch of the Simbol-X telescope, the soft  $\gamma$ -ray band remains unexplored. It is however this energy band which may provide the key for the understanding of the cosmic background radiation. Synthesis models, which are well established and tested against observational results, can be used to evaluate the integrated AGN contribution to the soft  $\gamma$ -ray background. However, the spectral shape of the different classes of AGN that are used for modelling the background has so far not been firmly established at soft  $\gamma$ -ray energies. As an illustration, Fig. 3 shows the impact of the AGN power law cut-off energy on the resulting prediction of the cosmic background radiation. Observations by BeppoSAX [31, 29] of a handful of radio quiet sources, loosely locate this drop-off in the range 30–300 keV; furthermore these measurements give evidence for a variable cut-off energy and suggest that it may increase with increasing photon index [29]. In radio loud sources the situation is even more complicated with some objects showing a power law break and others no cut-off up to the MeV region. In a couple of low luminosity AGN no cut-off is present up to 300–500 keV. The overall picture suggests some link with the absence (low energy cut-off) or presence (high energy cut-off) of jets in the various AGN types sampled, but the data are still too scarce for a good understanding of the processes involved.

Therefore, a goal of GRI is to measure the soft  $\gamma$ -ray Spectral Energy Distribution (SED) in a sizeable fraction of AGN in order to determine average shapes in individual classes and so the nature of the radiation processes at the heart of all AGN. This would provide at the same time information for soft  $\gamma$ -ray background synthesis models. On the other hand, sensitive deep field ob-



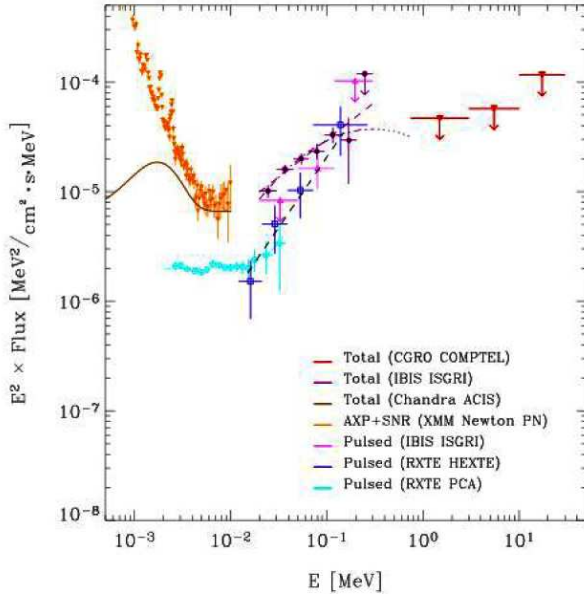


Figure 4. High-energy emission spectrum from the AXP 1E 1841-045 and the surrounding SNR Kes 73 [22]. The COMPTEL upper limits indicate that the spectra should break between 150–1000 keV.

servations should be able to resolve the soft  $\gamma$ -ray background into individual sources, allowing for the ultimate identification of the origin of the emission.

### 3.4. Particle acceleration in extreme B-fields

The strong magnetic fields that occur at the surface of neutron stars in combination with their fast rotation make them powerful electrodynamic particle accelerators, which may manifest themselves to the observer as pulsars. Gamma-ray emitting pulsars can be divided into 3 classes: spin-down powered pulsars, accretion powered pulsars, and magnetically powered pulsars, also known as magnetars.

Despite the longstanding efforts at understanding the physics of spin-down powered pulsars, the site of the gamma-ray production within the magnetosphere (outer gap or polar cap) and the physical process at action (synchrotron emission, curvature radiation, inverse Compton scattering) remain undetermined. Although most of the pulsars are expected to reach their maximum luminosity in the MeV domain, the relatively weak photon fluxes have only allowed the study of a handful of objects so far. Increasing the statistics will enable the study of the pulsar lightcurves over a much broader energy range than today, providing crucial clues to the acceleration physics of these objects.

Before the launch of INTEGRAL, the class of anomalous X-ray pulsars (AXPs), suggested to form a subclass of the magnetar population, were believed to exhibit very soft X-ray spectra. This picture, however,

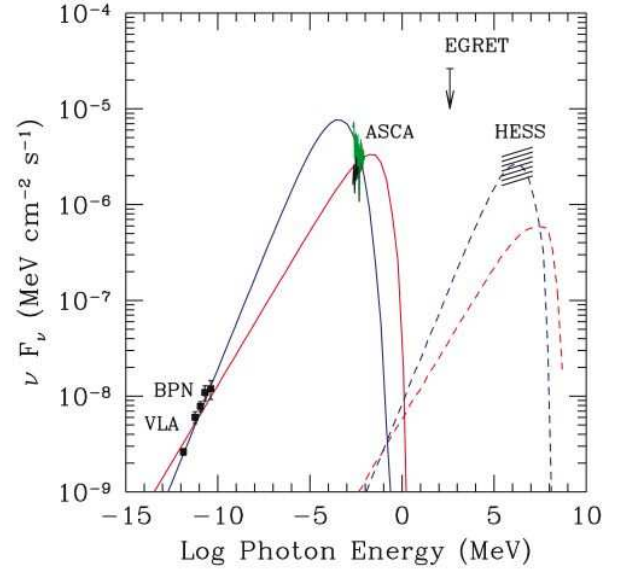


Figure 5. Broad-band emission spectrum of HESS J1813-178 assuming that all of the flux originates from the shell of SNR G12.8+0.0. Broad-band models based on a primary synchrotron peak and a secondary inverse Compton peak that fit these data points are superimposed [5].

changed dramatically with the detection of AXPs in the soft gamma-ray band by INTEGRAL [21, 22]. In fact, above  $\sim 10$  keV a dramatic upturn is observed in the spectra which is expected to peak in the 100 keV – 1 MeV domain (see Fig. 4). The same is true for Soft Gamma-ray Repeaters (SGRs), as illustrated by the recent discovery of quiescent soft gamma-ray emission from SGR 1806-20 by INTEGRAL [28]. The process that gives rise to the observed gamma-ray emission is still unknown. No high-energy cut-off has so far been observed in the spectra, yet upper limits in the MeV domain indicate that such a cut-off should be present. Determining what happens in the region of this cut-off may provide important insights in the physical nature of the emission process, and in particular, about the role of QED effects, such as photon splitting, in the extreme magnetic field that occur in such objects. Strong polarization is expected for the high-energy emission from these exotic objects, and polarization measurements may be crucial in disentangling the nature of the emission process and the geometry of the emitting region. Measurements of cyclotron features in the spectra will provide the most direct measure of the magnetic field strengths, complementing our knowledge of the physical parameters of the systems.

### 3.5. Broad-band gamma-ray emitters

The recent advent of the ground-based gamma-ray telescopes HESS and MAGIC, operating in the TeV regime, has revealed a substantial number of previously unknown high-energy gamma-ray sources in the galactic plane.

The detection of such a new population of galactic GeV–TeV gamma-ray emitters has opened a new window for studies of cosmic particle accelerators. Different types of sources have been identified as potential counterparts of the high-energy emitters: isolated pulsars and their pulsar wind nebulae (PWN), supernova remnants (SNR), star forming regions, and binary systems with a collapsed object like a microquasar or a pulsar.

For some of the sources observed at TeV energies, hard X-ray and soft gamma-ray emission has been detected by INTEGRAL [32, 25], indicating that the emission can be explained by a synchrotron inverse Compton mechanism. Yet, attempts to model the broad-band spectrum have so far been unsatisfactory (cf. Fig. 5) [5, 1]. Other sources do not show any hint of radio and/or X-ray emission, suggesting that the accelerated particles may be nucleons rather than electrons. Such a conclusion would be challenging, since for the first time, it would provide direct evidence for the sources of the main component of the cosmic-ray particle spectrum.

It is therefore clear that a better understanding of the emission mechanisms of the newly discovered HESS sources requires a high-sensitivity broad-band coverage of the entire high-energy band, from X-rays over hard X-rays, soft gamma-rays up to the GeV and TeV domain. Observations of TeV sources by GRI (and also of the GeV populations that will likely be discovered by AGILE or GLAST), will be crucial for the understanding of their emission mechanisms.

## 4. THE GRI MISSION

### 4.1. Mission requirements

Based on our scientific goals, we summarise the GRI mission requirements in Table 1. The major requirement for GRI is sensitivity. Many interesting scientific questions are in a domain where photons are rare, and therefore large collecting areas are needed to perform measurements in a reasonable amount of time<sup>1</sup>. It is clear that a significant sensitivity leap is required if the above listed scientific questions are to be addressed.

With such a sensitivity leap, the expected number of observable sources would be large, implying the need for good angular resolution to avoid source confusion in crowded regions, such as for example the galactic centre. Also, it is desirable to have an angular resolution comparable to that at other wavebands, to allow for source identification and hence multi-wavelength studies.

Gamma-ray emission may be substantially polarized due to the non-thermal nature of the underlying emission processes. Studying not only the intensity and the spectrum but also the polarization of the emission would add a new powerful scientific dimension to the observations. Such

Table 1. GRI mission requirements (sensitivities are for 100 ks and a detection significance of  $3\sigma$ ).

Parameter	Requirement	Goal
Energy band (keV)	50 – 900	50 - 1300
Continuum sensitivity <sup>a</sup>	$10^{-7}$	$3 \times 10^{-8}$
Narrow line sensitivity <sup>b</sup>	$3 \times 10^{-6}$	$10^{-6}$
Energy resolution	3%	0.5%
Field of view	5°	10°
Angular resolution	60''	30''
Time resolution	100 $\mu$ s	100 $\mu$ s
Polarization MDP <sup>c</sup>	5%	1%

<sup>a</sup>units:  $\text{ph cm}^{-2}\text{s}^{-1}\text{keV}^{-1}$

<sup>b</sup>units:  $\text{ph cm}^{-2}\text{s}^{-1}$

<sup>c</sup>Minimum detectable polarization for 10 mCrab in 100 ks

measurements would allow the discrimination between the different plausible emission processes at work, and would constrain the geometry of the emission sites.

### 4.2. GRI design

The key element of GRI is a broad-band gamma-ray lens based on the principle of Laue diffraction of photons in mosaic crystals. Each crystal can be considered as a little mirror which deviates  $\gamma$ -rays through Bragg reflection from the incident beam onto a focal spot. Although the Bragg relation

$$2d \sin \theta = n \frac{hc}{E} \quad (1)$$

holds only for one specific energy  $E$  and its multiples, the mosaic spread  $\Delta\theta$  that occurs in the crystal leads to an energy spread  $\Delta E \propto \Delta\theta E^2$  ( $d$  is the crystal lattice spacing,  $\theta$  the Bragg angle,  $n$  the diffraction order,  $h$  the Planck constant,  $c$  the speed of light and  $E$  the energy of the incident photon). Placing the crystals on concentric rings around an optical axis, and careful selection of the inclination angle for each of the rings, allows then to build a broad-band gamma-ray lens that has continuous energy coverage over a specified band. Since larger energies  $E$  imply smaller diffraction angles  $\theta$ , crystals diffracting large energies are located on the inner rings of the lens. Conversely, smaller energies  $E$  are diffracted by crystals located on the outer rings.

Several considerations lead us to consider a minimum energy of  $\sim 200$  keV for the Laue lens. Below this energy, the band pass for individual crystals becomes very small, requiring an enormous number of crystal tiles to provide a continuum energy coverage. In addition, machining constraints will probably not allow the use of crystals that are thinner than  $\sim 1$ – $2$  mm, hence for energies below  $\sim 200$  keV, absorption of  $\gamma$ -rays starts to reduce the efficiency of the lens.

<sup>1</sup>We baseline as a typical observing time 100 ks

The upper energy of the Laue lens is basically set by the focal length of the telescope and the smallest radius that can be covered with crystal tiles. Mosaic defocusing, i.e. the spread of the focused gamma-ray beam due to the mosaicity of the crystals, becomes important for focal lengths exceeding  $\sim 100$  metres, reducing the sensitivity gain of the instrument. In addition, for a given energy, the radius on which a given crystal has to be placed to focus on the focal spot increases linearly with the focal length. Thus, the minimum energy of the Laue lens drives the total lens diameter. Fixing the minimum energy at  $\sim 200$  keV and the lens diameter at  $\lesssim 4$  metres, results in a focal length of 60–80 m and a maximum energy of  $\sim 1$  MeV.

The most promising technology for realizing such a long focal length is formation flying of two satellites, one carrying the lens and the other the detector. The focal distance has to be kept to within  $\pm 10$  cm in order to maintain the optimum performances of the instrument. The size of the focal spot is primarily determined by the size of the crystal tiles (between  $1 \times 1$  cm<sup>2</sup> and  $2 \times 2$  cm<sup>2</sup>) and the mosaic spread  $\Delta\theta$  of the crystals (1 arcmin at a distance of 100 m corresponds to a size of 3 cm). Thus the maximum allowed lateral displacement of the detector spacecraft with respect to the lens optical axis will be of the order of  $\pm 1$  cm. Considering the pointing precision, an accuracy of  $\sim 15$  arcsec are sufficient to maintain the system aligned on the source.

Crystals that we currently have under consideration are copper and germanium. Germanium crystals have been employed for the CLAIRE balloon lens, which was used to demonstrate the first-ever detection of a gamma-ray source by a crystal lens telescope [33]. Copper crystals are currently fabricated at ILL (Grenoble) with the required mosaicities, and laboratory measurements indicate that they fulfil our efficiency requirements [12]. We are also studying the possibility of using gradient or bent crystals with the aim of substantially increasing the diffraction efficiencies [2]. Another possibility is the use of silver or gold crystals, which provide good diffraction efficiencies at much less weight than copper.

Although the lens is basically a radiation concentrator (with a beam size that corresponds to the crystal mosaicity, say  $\sim 1$  arcmin), it has a substantial off-axis response. For sources situated off the optical axis, the focal spot will turn into a ring-like structure (which is centred on the lens optical axis), with an azimuthal modulation that reflects the azimuthal angle of the incident photons. Thus, the arrival direction of off-axis photons can be reconstructed from the distribution of the recorded events on the detector plane. The field-of-view of the lens is therefore basically restricted by the size of the detector. For a detector size of  $30 \times 30$  cm<sup>2</sup> and a focal length of 100 m the field-of-view amounts to  $\sim 15$  arcmin. Within this field-of-view the lens can be used as an (indirect) imaging device. The imaging performances can be considerably improved by employing a dithering technique, similar to that employed for INTEGRAL.

It is important to notice that a Laue lens will not significantly alter the polarization of the incident radiation. In other words, a polarized gamma-ray beam will still be polarized after concentration on the focal spot, and the use of a polarization sensitive detector will allow for polarization measurements. In view of the expected polarization of non-thermal emission, this aspect of GRI opens a new discovery space which will considerably improve our understanding of the observed objects.

To profit to the full from the gamma-ray lens, we employ a position sensitive detector in the focal spot. Our actual design studies are mainly focused on a pixelised stack of detector layers, which on the one hand has the required position sensitivity, and on the other hand can be exploited as Compton telescope for instrumental background reduction. Possible detector materials under investigation are CdTe, CZT, Si, and/or Ge [7, 35]. Although Germanium would provide the best energy resolution (and is certainly the preferred option for detailed studies of gamma-ray lines), the related cooling and annealing requirements may drive us towards other options.

In order to extend the GRI energy coverage towards energies below  $\sim 200$  keV we plan to add a hard X-ray telescope to the mission. Such a broad-band coverage is crucial for the understanding of compact objects physics, since such sources exhibit generally temporal spectral variations over a wide energy band. In particular, the accurate determination of energy cut-offs will rely on an accurate determination of the broad-band spectrum of the object under investigation.

The American NuStar mission or the French-Italian Symbol-X mission plan to use double-reflection mirrors up to energies of  $\sim 80$  keV to cover the hard X-ray band. We propose the usage of a single-reflection multilayer-coated concentrator to cover the  $\sim 50$ –200 keV energy band, providing thus a continuous energy coverage over (at least) the 50–900 keV energy band for the GRI mission. Our model calculations, which are based on measured optical constants, predict good effective areas of the concentrator up to  $\sim 200$  keV and even above [8]. As substrate, we propose the usage of high-precision Si-pore optics that are currently developed by ESA in the context of the XEUS mission [4].

## 5. CONCLUSIONS

The gamma-ray band presents a unique astronomical window that allows the study of the most energetic and most violent phenomena in our Universe. With ESA's INTEGRAL observatory, an unprecedented global survey of the soft gamma-ray sky is currently performed, revealing hundreds of sources of different kinds, new classes of objects, extraordinary views of antimatter annihilation in our Galaxy, and fingerprints of recent nucleosynthesis processes. While INTEGRAL provides the long awaited global overview over the soft gamma-ray sky, there is a growing need to perform deeper, more focused investiga-



tions of gamma-ray sources, comparable to the step that has been taken in X-rays by going from the EINSTEIN satellite to the more focused XMM-Newton observatory. Technological advances in the past years in the domain of gamma-ray focusing using Laue diffraction techniques have paved the way towards a future gamma-ray mission, that will surpass past missions by large factors in sensitivity and angular resolution. Such a future *Gamma-Ray Imager* will allow the study of particle acceleration processes and explosion physics in unprecedented depth, providing essential clues to the intimate nature of the most violent and most energetic processes in the Universe.

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